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AN EVALUATION OF THE KNOCK-LIMITED PERFORMANCE OF TRIPTANE

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NACA AIRCRAFT ENGINE RESEARCH LABORATORY

MEMORANDUM REPORT

for the

Air Technical Service Command, Army Air Forces

AN EVALUATION OF THE KNOCK-LIMITED PERFORMANCE OF TRIPTANE

By Henry C. Barnett

SUMMARY

An analysis is made of data obtained in an experimental investigation of the knock-limited performance of triptane. Data obtained in the F-3 and F-4 rating engines, two full-scale air-cooled aircraft cylinders, and flight tests of a full-scale multicylinder engine are discussed. As a means of evaluating triptane, use is made of the relation between compression densities and temperatures as well as the reciprocal blending equation used in previous NACA reports. The knock-limited performance of triptane is expressed in terms of F-3 and F-4 ratings, alkylate-replacement values, sensitivity to different degrees of engine severity, and lead susceptibility.

INTRODUCTION

In 1943 the Air Technical Service Command, Army Air Forces, requested the NACA to undertake a program to evaluate the antiknock qualities of triptane. This program, conducted at the Cleveland laboratory, was to include studies of the knock-limited performance characteristics of triptane in laboratory small-scale engines, full-scale single cylinders, and full-scale multicylinder engines on the test stand and in flight.

The scope of this program required an extensive investigation of fundamental characteristics of fuel performance and for this reason the quantity of data obtained is necessarily very large. The present report is designed not to discuss the entire triptane program but rather to present data comparing antiknock qualities of triptane with antiknock qualities of other fuels. In the presentation of these data several fundamental relations are used and references are cited for more detailed information on these relations. It is emphasized that this evaluation considers the advantages and disadvantages of triptane with regard only to antiknock quality.

CONVENTIONAL KNOCK RATINGS

On the basis of current knowledge of fuel performance in various engines it is impossible to assign a single value to a fuel and thereby indicate its performance relative to other fuels in all engines and at all operating conditions. In the absence of a method of obtaining a universal rating, the most logical approach to the problem of rating any fuel is to test that fuel in standard rating engines at conditions accepted by laboratories throughout the United States.

Inasmuch as the F-3 and F-4 rating methods fall into this category, the first step in the present evaluation of triptane is to examine the F-3 and F-4 data obtained and to make a comparison of triptane with other high-antiknock blending agents. The ratings for this comparison are shown in the following table:

F-3 AND F-4 PERFORMANCE RATINGS FOR VARIOUS AVIATION FUEL COMPONENTS

[Data from reference 1; all fuels contain 4 ml TEL/gal; F-4 ratings are for a fuel-air ratio of 0.11.]

Fuel	Performance number	
	F-3	F-4
Methyl *tert*-butyl ether	>161	>161
Paraffins:		
Triptane	149	>161
Diisopropyl	142	>161
Hot-acid octane	127	>161
Neohexane	161	159
Isopentane	[a]125	>138
Alkylate	119	137
Aromatics:		
Mixed xylenes	124	>161
Toluene	118	>161
Cumene	85	>161
Benzene	[b]68	>161

[a]The F-3 performance number for a blend containing 40 percent (by volume) isopentane, 60 percent alkylate, and 4 ml TEL/gal was 125. The high vapor pressure of isopentane prevented any determination for blends of higher concentration.

[b]By definition F-3 rating of benzene is 87 octane number, or 68 performance number. Tests have shown that the addition of tetraethyl lead to benzene does not appreciably change its F-3 rating.

F-3 ratings were determined for all pure fuels (leaded to 4 ml TEL/gal) with the exception of methyl *tert*-butyl ether and isopentane. The rating of the ether exceeded the upper limit (161) of the performance-number scale and the isopentane could not be satisfactorily determined because of its high vapor pressure. In the case of the F-4 ratings only two of the fuels fell below the upper limit of the performance-number scale; the relative merits of the various fuels cannot therefore be obtained from these data.

Sufficient data were obtained on the F-4 engine, however, to permit an extrapolation of the performance-number scale above 161. This extrapolation is explained in reference 1. Furthermore, before ratings could be assigned to triptane and isopentane (both leaded to 4 ml TEL/gal), it was necessary to estimate the corresponding values of knock-limited indicated mean effective pressure. These values were determined by applying data (from reference 1) for blends below 100-percent concentration to the reciprocal blending equation described in reference 2. By use of these extrapolations the antiknock ratings of the paraffinic fuels (leaded to 4 ml TEL/gal) tested in the F-4 engine at a fuel-air ratio of 0.11 were found to be as follows:

Fuel	F-4 performance number
Triptane	360
Diisopropyl	202
Hot-acid octane	197
Neohexane	159
Isopentane	144
Alkylate	137

Inasmuch as the reciprocal blending equation (reference 2) applies to neither aromatics nor methyl tert-butyl ether, performance numbers for these compounds were not estimated. It should also be noted that the F-4 performance numbers in the foregoing discussion were not obtained by direct matching but by comparison of knock-limited indicated mean effective pressures with a previously established rating scale. (See reference 1.)

The F-4 (rich) data indicate that triptane leaded to 4 ml TEL per gallon has a higher rich performance number (360) than any other paraffinic fuel (leaded) tested. It is probable, however, that some of the aromatics and the methyl tert-butyl ether have ratings equal to or greater than the F-4 rating for triptane. The F-3 (lean) rating of triptane exceeded all of the test fuels examined except methyl tert-butyl ether and neohexane. The F-3 rating for neohexane (leaded to 4 ml TEL/gal) reported in reference 1 is higher than most ratings for this fuel reported in other references.

BLENDING VALUES

As previously stated the F-4 indicated-mean-effective-pressure ratings of several of the paraffinic fuels (including triptane) were estimated by use of the reciprocal blending equation of reference 2.

The estimation for triptane leaded to 4 ml TEL per gallon is illustrated in figure 1 for a fuel-air ratio of 0.11. In this figure the composition (by volume) of the various blends tested is shown along the abscissa and the knock-limited indicated mean effective pressure is shown along the ordinate, which is an inverted reciprocal scale. Three curves illustrate the manner in which successive additions of triptane increase the knock-limited performance of three different base stocks. Because of engine limitations, blends containing more than 60 percent triptane were not tested at this fuel-air ratio.

The data in figure 1 show that the relation between composition and the reciprocal of the knock-limited indicated mean effective pressure is approximately linear for the range of compositions examined and that extrapolations of these three curves result in a common point of intersection representing the knock-limited indicated mean effective pressure of 100 percent triptane. Data obtained in a full-scale single cylinder (fig. 2) further substantiate this relation for triptane and other paraffinic fuels. The data for neohexane in figure 2 have not been previously published. Data for the other fuels are presented in reference 3. It is concluded from these data that triptane is no different from other paraffinic fuels with regard to the applicability of the reciprocal blending equation.

In addition to serving as a test of the blending equation, experimental data (reference 1) obtained in the F-3 and F-4 engines were used to prepare performance charts for ternary fuel blends. Two such charts are presented in figures 3 and 4 for ternary blends containing triptane; similar charts for other high-performance fuels are given in reference 1. Points shown on these figures represent test blends used to check the accuracy of the charts. (See reference 1.) In order to compare these charts on a common basis, the concept of alkylate-replacement value has been used. The alkylate-replacement value is defined as barrels of replaced component equivalent to 1 barrel of the replacing component. Applied to the triangular charts (figs. 3 and 4) the alkylate-replacement value is the slope of a constant-performance line. In figure 3, for example, start with a blend of 92 percent alkylate and 8 percent virgin base stock having an F-3 rating of 115. Move along this constant-performance line until 10 percent triptane has been added. It can be seen that the addition of 10 percent triptane has replaced 17 percent alkylate; thus, the alkylate-replacement value of triptane is 1.7. The significance of the alkylate-replacement value is discussed in reference 4.

From the charts presented in reference 1 (F-3 and F-4 data) the replacement values have been calculated for the high-performance fuels investigated. Two sets of values are given: one for the case in which virgin base stock is the third component, as in figure 3, and one for the case in which one-pass catalytic stock is the third component, as in figure 4. The following table presents the values obtained:

High-performance component	Alkylate-replacement value with virgin base stock		Alkylate-replacement value with one-pass catalytic stock	
	F-3	F-4	F-3	F-4
Methyl tert-butyl ether	1.8	[a]4.4-3.8	1.4	[a]6.8-5.4
Paraffins:				
Triptane	1.7	2.7	1.5	6.3
Diisopropyl	1.5	1.9	1.6	3.6
Hot-acid octane	1.2	1.9	1.2	3.9
Neohexane	1.5	1.4	1.5	2.1
Isopentane	1.3	1.1	1.3	1.3
Aromatics:				
Mixed xylenes	---------	[a]2.0-2.4	---------	6.3
Toluene	.7	3.8	1.5	[a]6.8-5.8
Cumene	.3	[a]2.5-2.6	---------	--------
Benzene	.4	2.8	.4	6.2

[a]For these fuels the alkylate-replacement value varies with performance number. The particular values given are for blends having F-4 ratings of 130 to 150 performance number.

For the first case (fig. 3) triptane and methyl tert-butyl ether have the highest F-3 replacement values, the ether being slightly higher than triptane. Under F-4 conditions toluene and methyl tert-butyl ether have the highest values. By both the F-3 and F-4 methods triptane has a higher replacement value than any of the other paraffinic fuels.

For the second case (fig. 4) toluene, triptane, diisopropyl, and neohexane are highest and about equal in replacement value at F-3 conditions. At F-4 conditions toluene, methyl tert-butyl ether, benzene, triptane, and mixed xylenes are highest and about equal in replacement value. In this case triptane is about equal to or higher than the other paraffinic fuels by both the F-3 and F-4 methods.

LEAD SUSCEPTIBILITY

Small-scale engine data were obtained to provide information on the lead susceptibility of triptane in comparison with the lead susceptibility of other hydrocarbon fuels. These data (reference 5) are presented in figure 5. In this figure the lead susceptibility is defined as follows:

$$\text{Relative lead susceptibility} = \frac{\dfrac{\text{imep of hydrocarbon blend + 4 ml TEL/gal}}{\text{imep of S reference fuel + 4 ml TEL/gal}}}{\dfrac{\text{imep of hydrocarbon blend}}{\text{imep of S reference fuel}}}$$

The data in figure 5 show that the lead susceptibility of triptane is considerably lower than most of the aromatic hydrocarbons at both fuel-air ratios and both inlet-air temperatures shown. The lead susceptibility of triptane is slightly greater than that of S reference fuel at the conditions shown.

EFFECT OF ENGINE OPERATING CONDITIONS

Inasmuch as the order in which a given group of fuels will rate according to antiknock quality varies with the severity of engine operating conditions, an NACA program was conducted to determine the variation of knock-limited performance of triptane (and other fuels) with severity of engine conditions. The detailed results of this program are reported in references 6, 7, and 8.

In the course of the investigation a method of correlating knock-limited performance data at different inlet-air temperatures with similar data at different compression ratios was derived. The detailed development and use of this method is explained in reference 9. By this method the correlation of temperature and compression-ratio data is effected by plotting compression-air density against the compression temperature when the piston is at top center on the compression stroke. The formulas used for calculating the density and the temperature are as follows:

$$\rho = \frac{A(r-1)}{nV_d} = \frac{\text{imep} \times \text{isfc} \times (r-1)}{F/A \times 2.376 \times 10^7}$$

and

$$T = T_o r^{0.41}$$

where

ρ compression density

A air flow, pounds per minute

r compression ratio

n intake cycles per minute

V_d engine displacement volume, cubic inches

F fuel flow, pounds per minute

T compression temperature, $^{\circ}R$

T_0 intake-air temperature, $^{\circ}R$

In the application of the correlation to a given engine and spark advance the indicated specific fuel consumption will depend primarily upon compression ratio; therefore, in the test results presented for variable inlet-air temperature and constant compression ratio, the density can be regarded as proportional to the indicated mean effective pressure.

Figure 6 (reference 10) presents the knock-limited indicated mean effective pressures of triptane at five compression ratios and five inlet-air temperatures as a function of fuel-air ratio. These data were used to compute the density-temperature curves of triptane presented in figure 7. At a compression ratio of 8.0 only three data points were obtained at an inlet-air temperature of 150° F and no data were recorded at lower inlet-air temperatures because of preignition. The curve for an inlet-air temperature of 150° F was therefore calculated from the density-temperature plot established from the variable-compression-ratio tests. Also, because of preignition difficulties, the test at an inlet-air temperature of 250° F and a compression ratio of 5.0 is subject to an error in indicated mean effective pressure of as much as 50 pounds per square inch at fuel-air ratios leaner than 0.08.

For comparison with triptane the density-temperature relations of several other fuels are included in figure 7, which shows very clearly how the various fuels are affected by changes in the severity of operating conditions. At a fuel-air ratio of 0.065, for example, triptane above a compression temperature T of 1500° R is more sensitive to increasing severity of conditions than any of the other fuels presented in figure 7. It is apparent, however, that up to a compression temperature of 1770° R, triptane is still the most desirable fuel because of its greater antiknock value. By the time the severity of conditions has been increased to a value corresponding to $T = 1950°$ R, triptane has depreciated so rapidly relative to other fuels that it is not so desirable from antiknock considerations as S reference fuel, toluene, aviation alkylate, or diisopropyl. In fact, at 1950° R triptane (leaded to 4 ml TEL/gal) is only slightly better than 28-R at this fuel-air ratio. At a fuel-air ratio of 0.11 (fig. 7(b)) a similar comparison can be made. Furthermore, if the curve for triptane in figure 7(b) can be smoothly extrapolated above $T = 1900°$ R it is noted that all of the other fuels shown will probably be better than triptane at values of T in excess of 2000° R.

Data obtained on the R-2600 single-cylinder test engine substantiate the fact that the performance of triptane depreciates at severe operating conditions. In figures 8 and 9, for example, the single-cylinder test data (unpublished) plotted at two fuel-air ratios and two conditions of spark timing show that the advantage in knock-limited performance to be gained by the addition of 20 percent triptane to 28-R are considerably less at the severe conditions than at the mild condition. Because the effects of cylinder-wall temperature, spark advance, and engine speed have not been included in this correlation method, no direct comparisons of temperature values presented in figures 7, 8, and 9 should be made.

MULTICYLINDER ENGINE TESTS

Tests (results unpublished) were made over a range of operating conditions in an R-1830 engine mounted on a test stand. The fuels used for these tests were 28-R and a blend containing 80 percent 28-R and 20 percent triptane. The final blend contained 4.6 ml TEL per gallon.

Over the range of conditions examined in these tests the increase in knock-limited power of 28-R due to the addition of 20 percent triptane varied between 17 and 29 percent at a fuel-air ratio of 0.065 and between 22 and 24 percent at a fuel-air ratio of 0.10. These results are in agreement with results obtained in flight tests of an R-1830 engine (reference 11).

SUMMARY OF RESULTS

Within the limitations of this evaluation of the knock-limited performance of triptane, the following results are apparent:

1. Triptane leaded to 4 ml TEL per gallon has an F-3 performance number of 149 and an extrapolated F-4 performance number of 360.

2. In comparison with paraffinic fuels (diisopropyl, hot-acid octane, neohexane, isopentane, and aviation alkylate) triptane had the highest F-3 rating (with the exception of neohexane) and the highest F-4 rating. Although the F-3 rating of methyl tert-butyl either (<166) could not be accurately determined, it was greater than the rating of triptane (149). The data for F-4 tests of four aromatics and methyl tert-butyl ether could not be accurately extrapolated; it is probable, however, that some of the aromatics and methyl tert-butyl ether have F-4 ratings equal to or greater than triptane.

3. Small-scale engine data at two inlet-air temperatures showed that the lead susceptibility of triptane at lean and rich fuel-air mixtures is considerably less than that of the aromatic fuels with which it was compared. The lead susceptibility of triptane is slightly greater than that of S reference fuel at the conditions examined.

4. Compression temperature-density data obtained on a small-scale engine and on an R-2600 full-scale single-cylinder test engine indicate that the knock-limited performance of triptane at the more severe conditions is sensitive to changes in operating conditions. In the small-scale engine tests at severe conditions, triptane leaded to 4 ml TEL per gallon had a lower knock-limited performance than S reference fuel, toluene, aviation alkylate, and diisopropyl (all leaded to 4 ml TEL/gal) at a fuel-air ratio of 0.065. In these same tests, however, the knock-limited performance of triptane was appreciably better than all fuels with which it was compared at mild conditions and both low and high fuel-air ratios. The R-2600 tests showed that under severe conditions the improvement in knock-limited performance to be gained by addition of 20 percent triptane to 28-R fuel was small.

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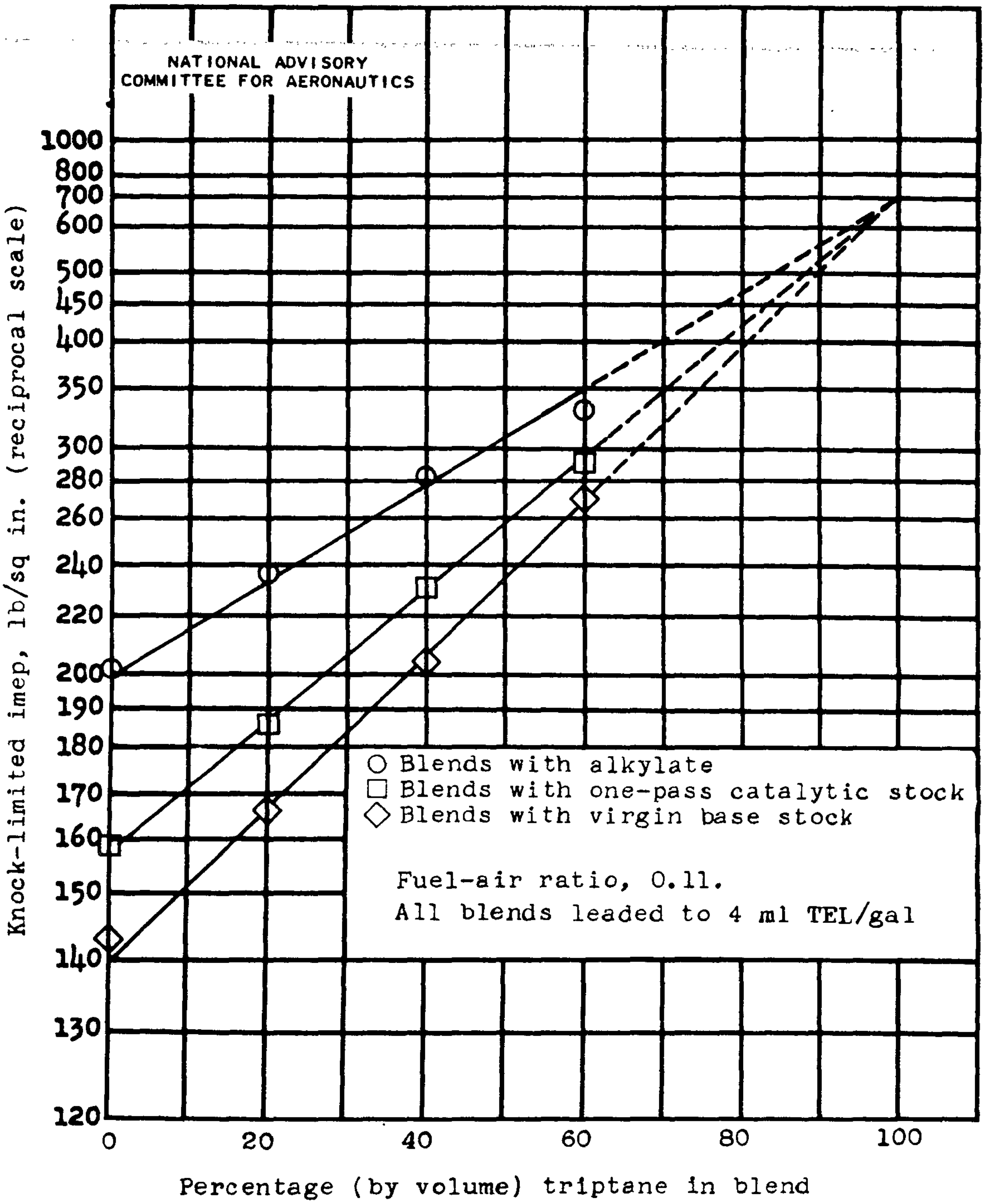
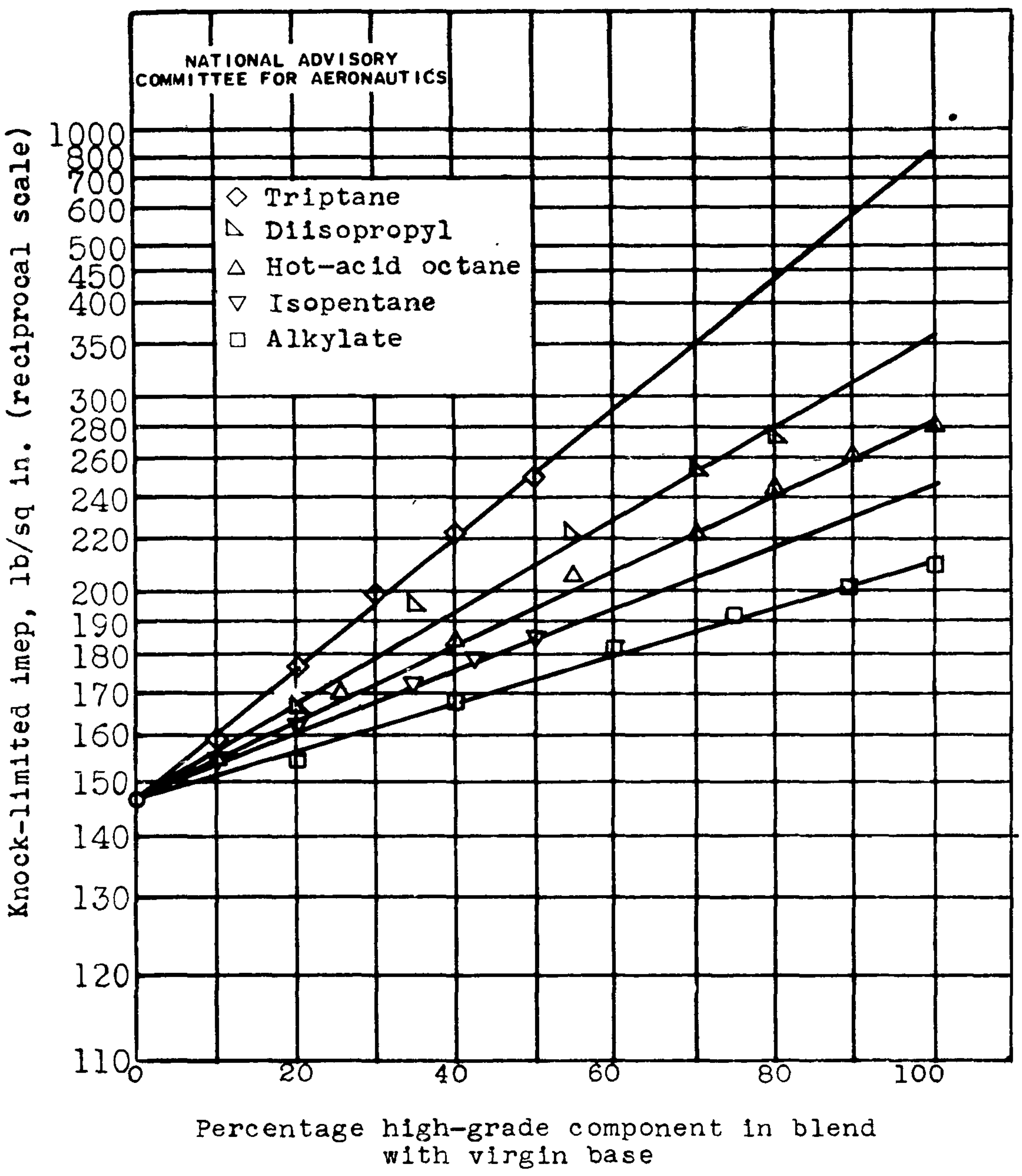
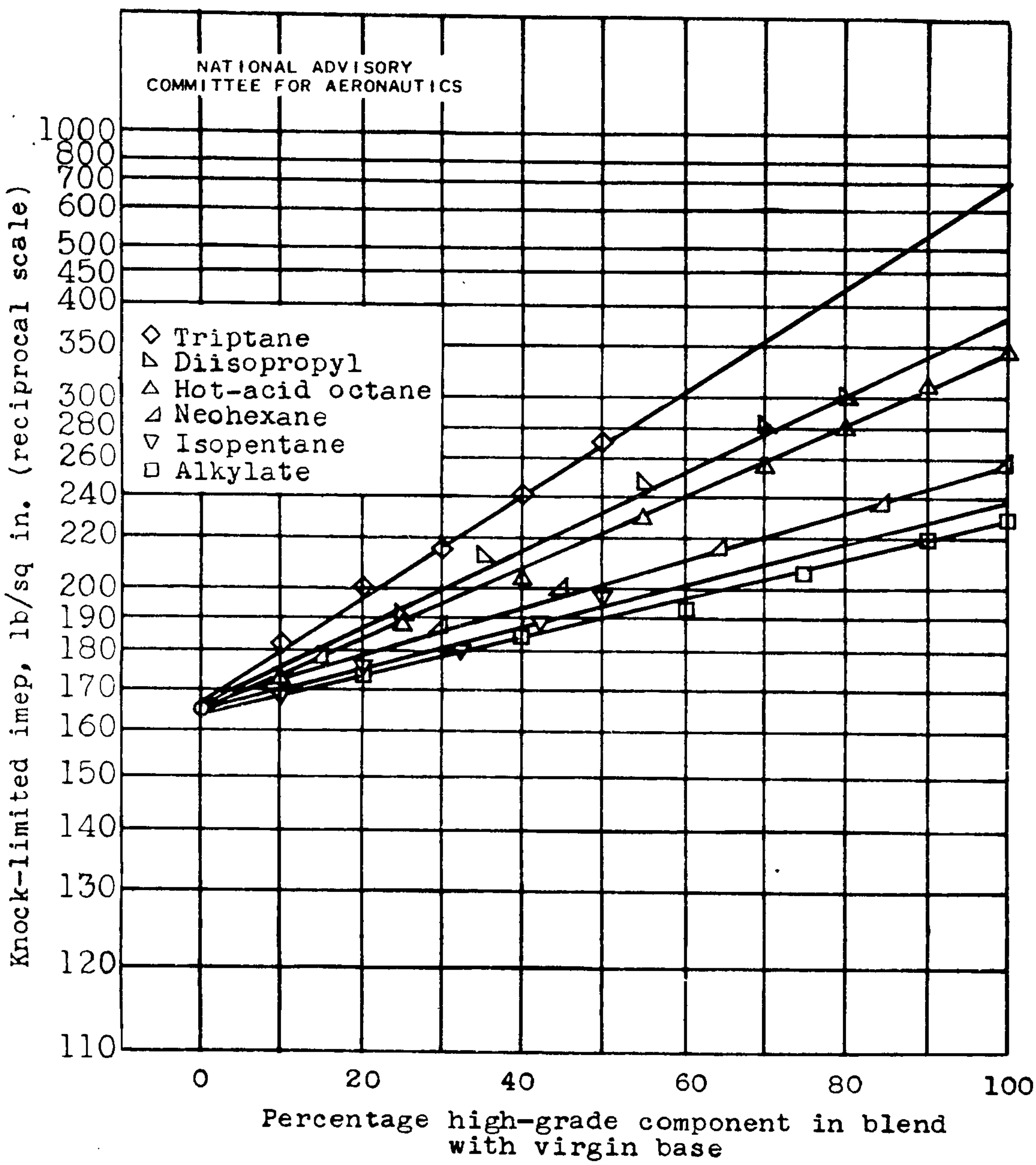


Figure 1. - Knock-limited performance of triptane in blends with virgin base stock, one-pass catalytic stock, and an aviation alkylate as determined by the F-4 rating method. Data from reference 1.



(a) Fuel-air ratio, 0.067.

Figure 2. - Knock-limited performance of blends of virgin base with selected fuel components; all containing 4 ml TEL per gallon. R-2800 cylinder; compression ratio, 7.7; spark advance, 20° B.T.C.; engine speed, 2000 rpm; inlet-mixture temperature, 240° F; cylinder-head temperature at exhaust end zone, 350° F. Data are from reference 3 with exception of neohexane data which are unpublished.



(b) Fuel-air ratio, 0.10.

Figure 2. - Concluded.

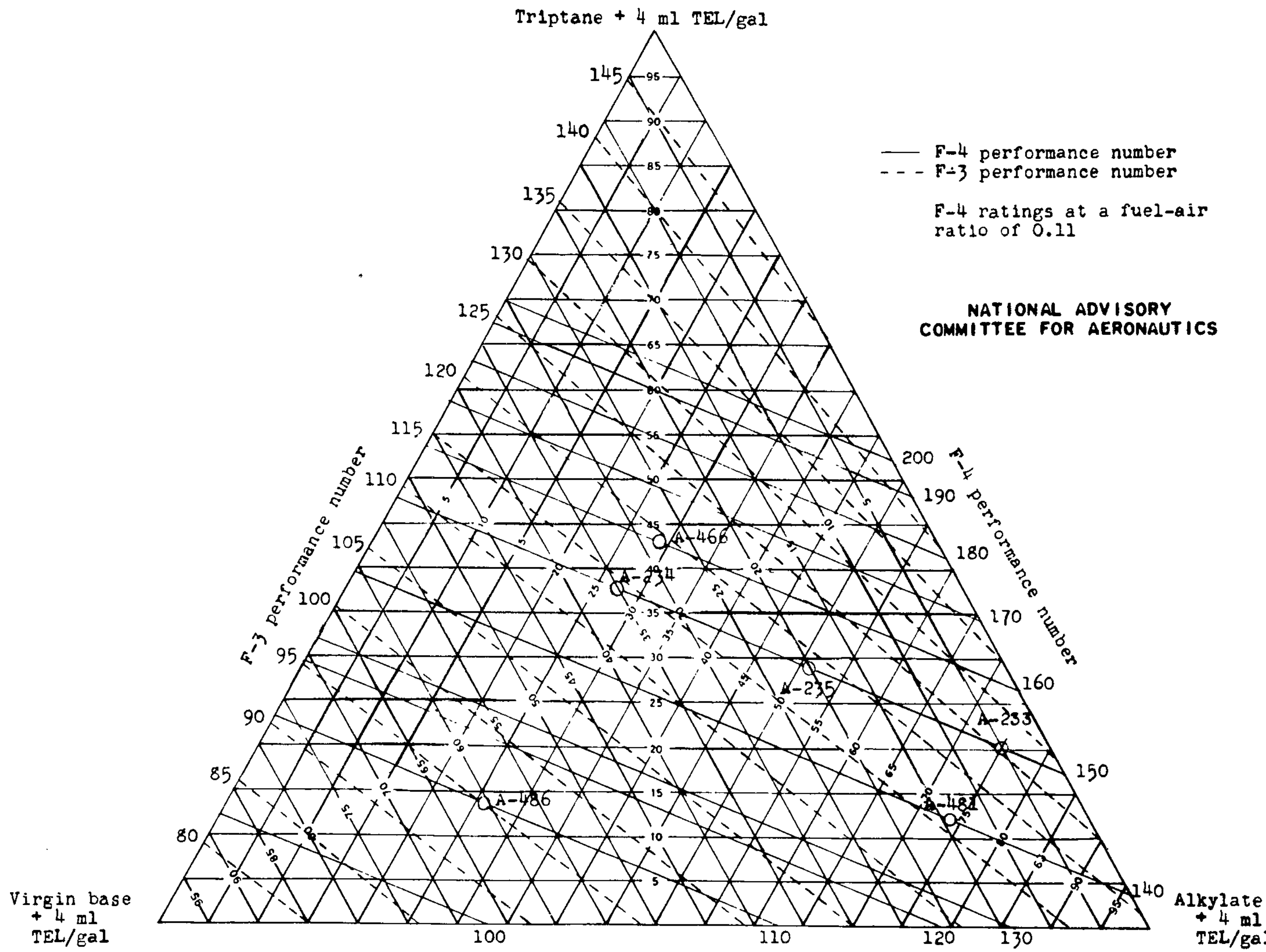


Figure 3. - Knock-limited performance determined by the F-3 and F-4 rating methods for ternary blends containing triptane, an aviation alkylate, and a virgin base stock. (Fig. 7(a) of reference 1.)

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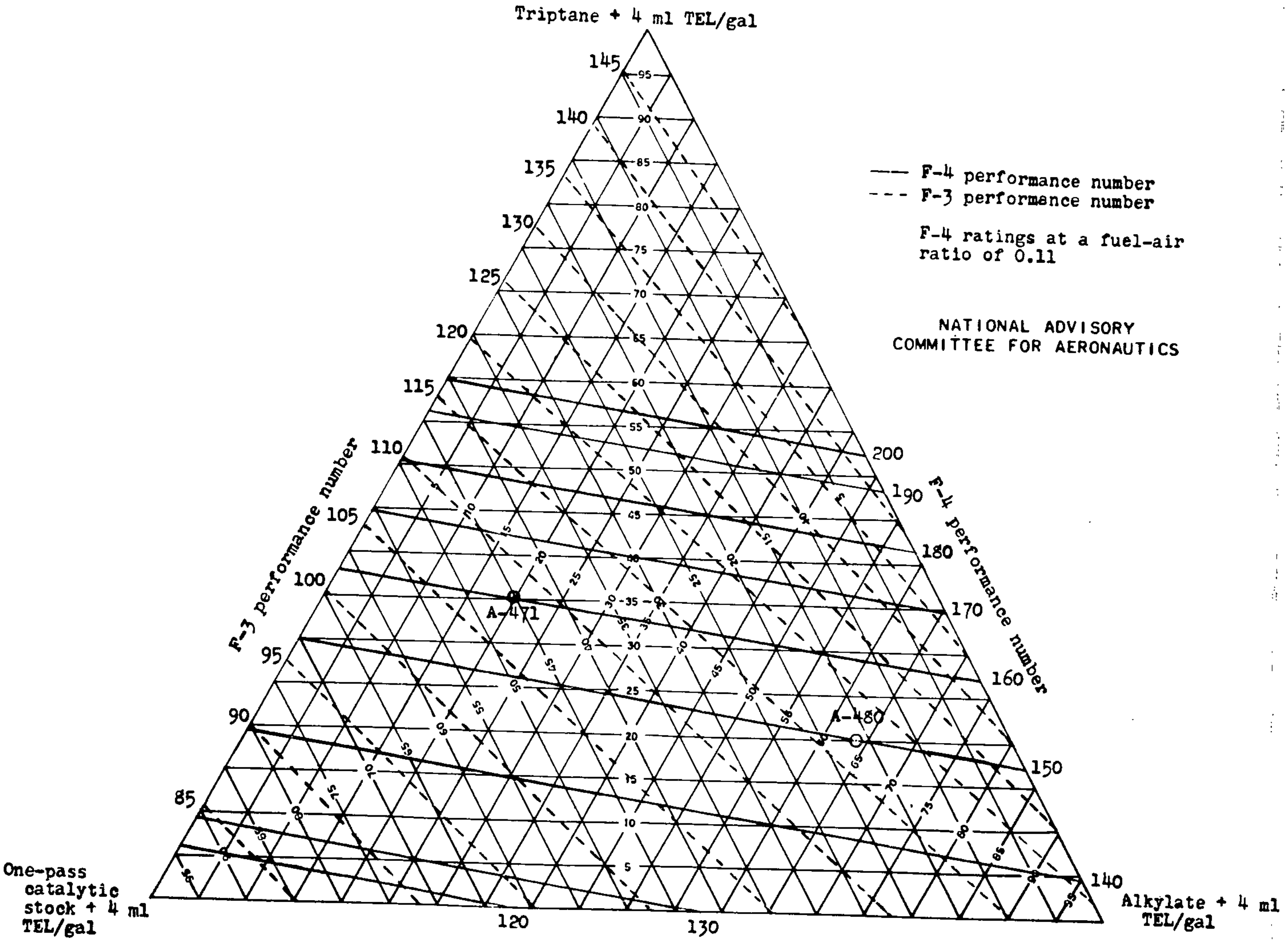

Figure 4. - Knock-limited performance determined by the F-3 and F-4 rating methods for ternary blends containing triptane, an aviation alkylate, and a one-pass catalytic stock. (Fig. 8(b) of reference 1.)

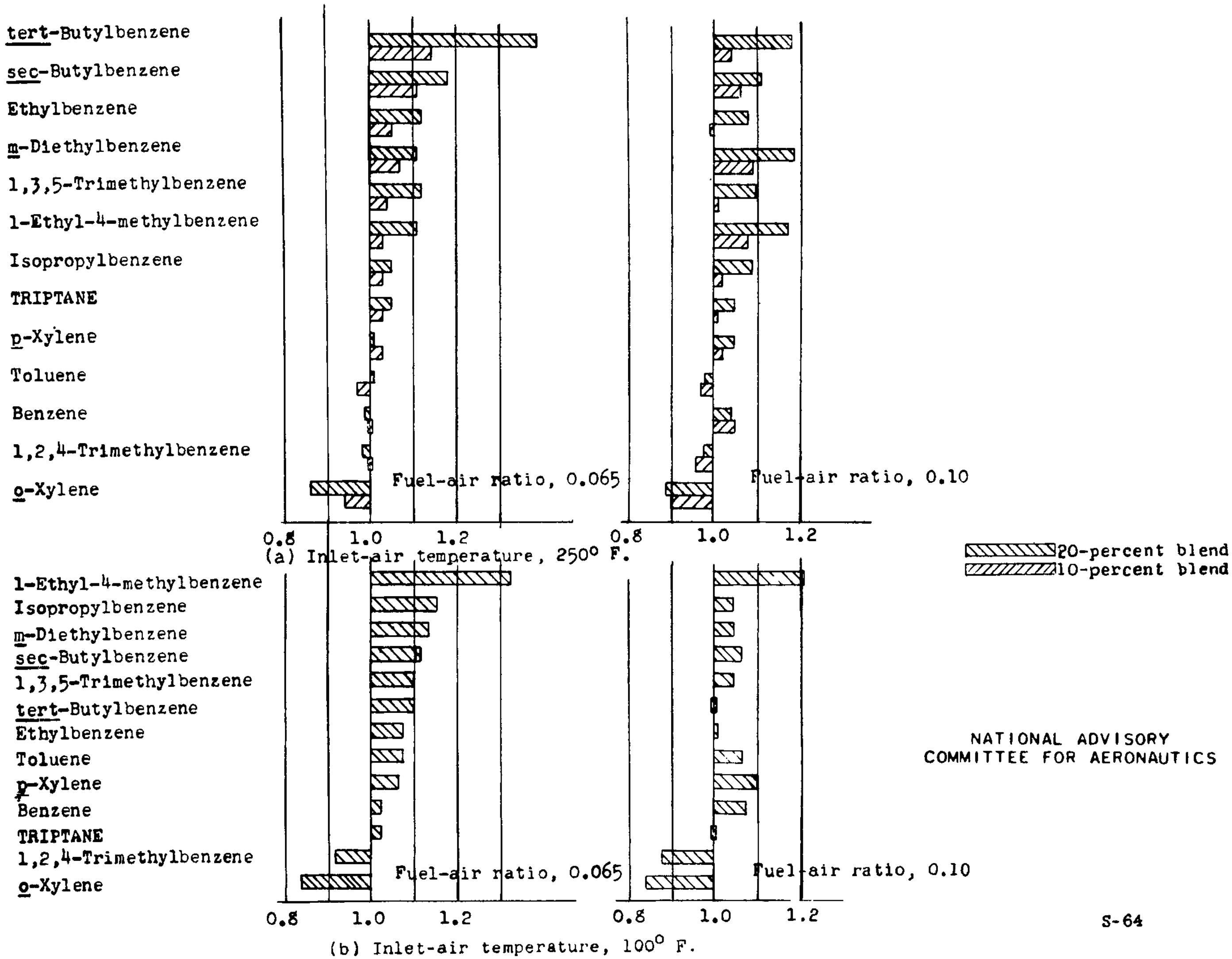

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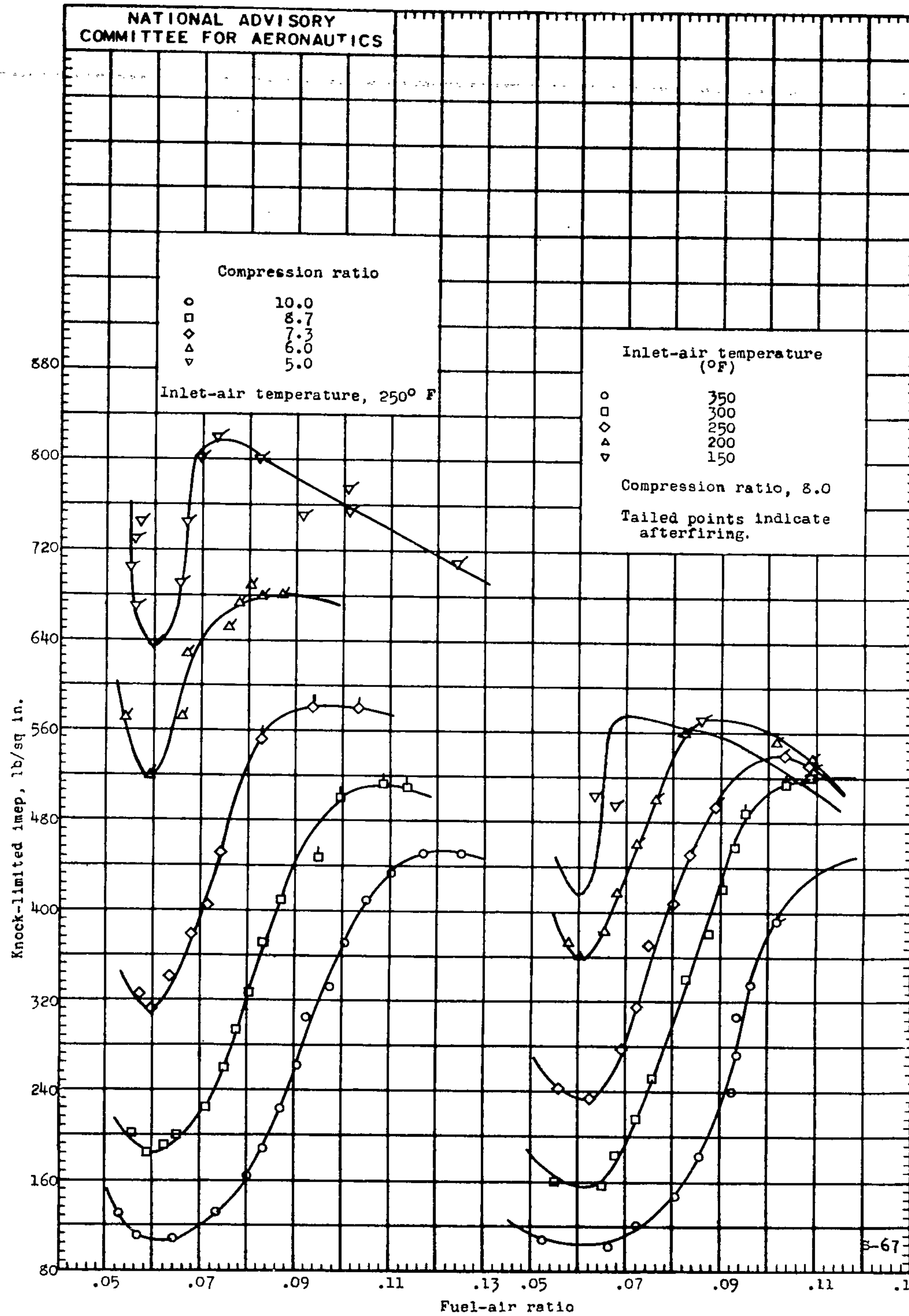
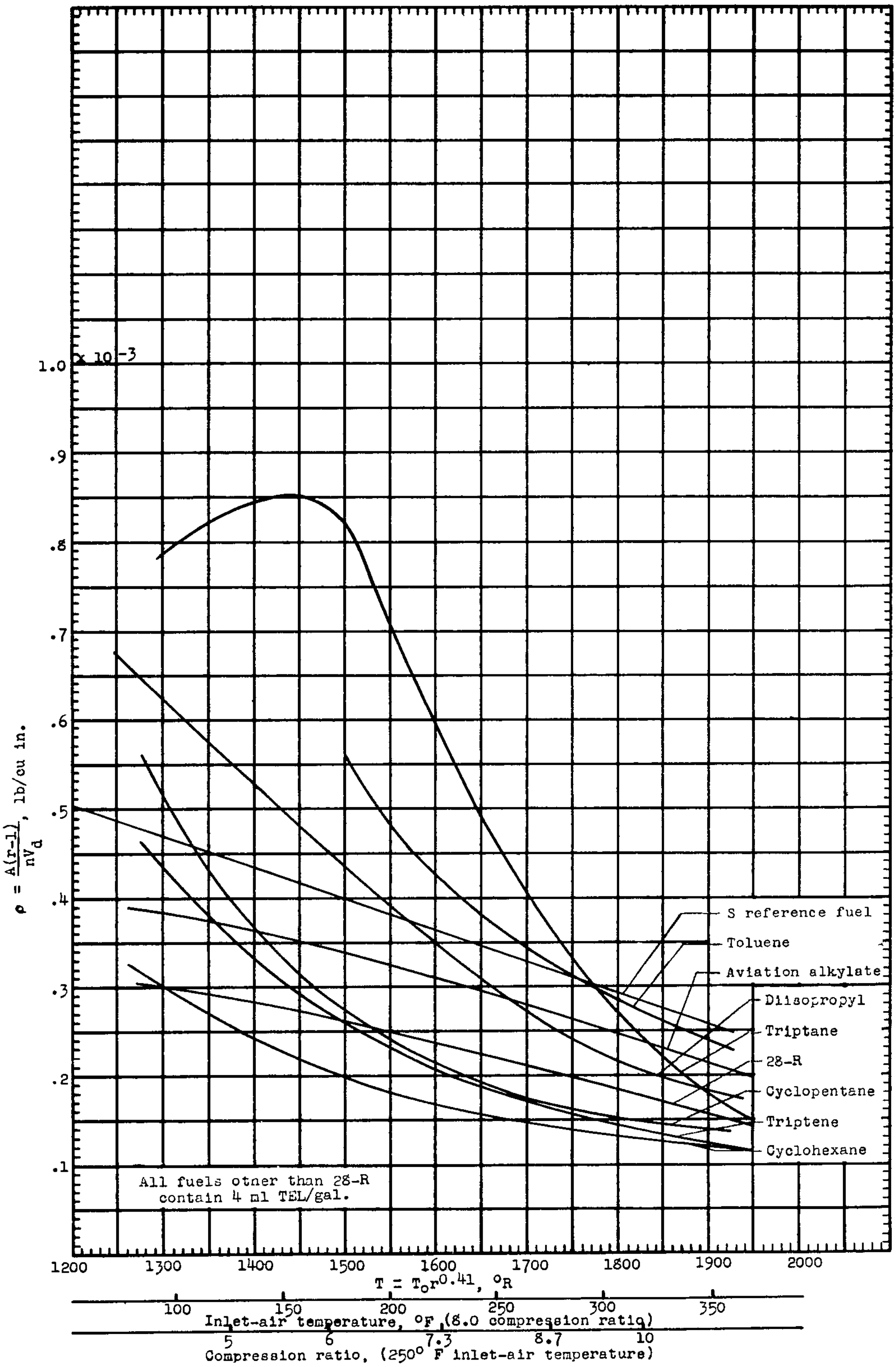
Figure 5. - Relative lead susceptibility (imep ratio of blends leaded to 4 ml TEL/gal to imep ratio of unleaded blends) of triptane and 12 aromatics in S reference fuel as determined in a 17.6 engine. (Fig. 18 of reference 5.)



(a) Variable compression ratio.

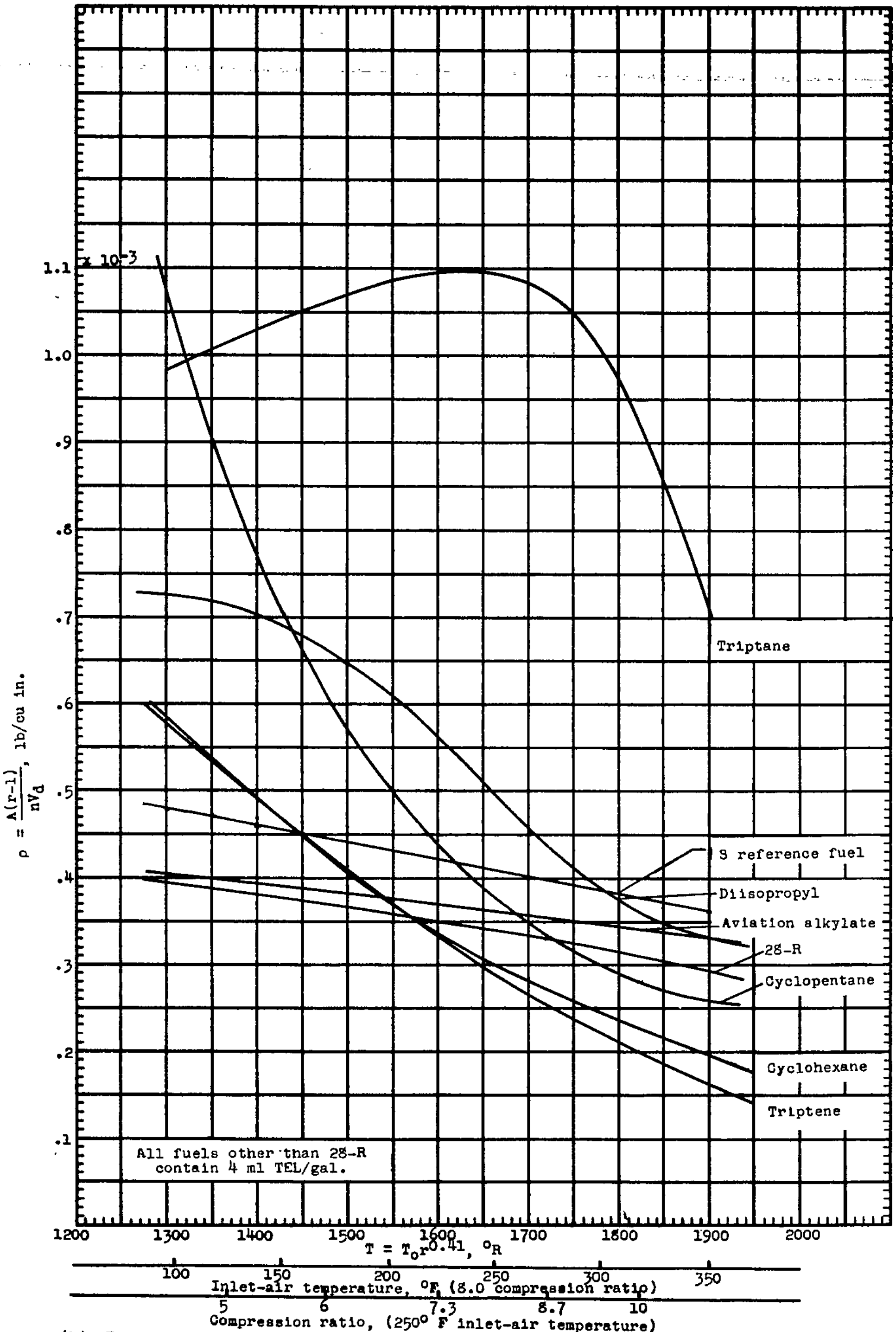
(b) Variable inlet-air temperature.

Figure 6. - The effect of compression ratio and inlet-air temperature on the knock-limited performance of triptane plus 4 ml TEL per gallon. CFR engine; four-hole cylinder; engine speed, 1800 rpm; spark advance, 30° B.T.C.; coolant temperature, 250° F. (Taken from fig. 8 of reference 10.)



(a) Fuel-air ratio, 0.065.

Figure 7. - Temperature-density relations for various fuels. CFR engine; four-hole cylinder; engine speed, 1800 rpm; spark advance, 30° B.T.C.; coolant temperature, 250° F; compression ratio, variable; inlet-air temperature, variable.



(b) Fuel-air ratio, 0.10.

Figure 7. - Concluded.

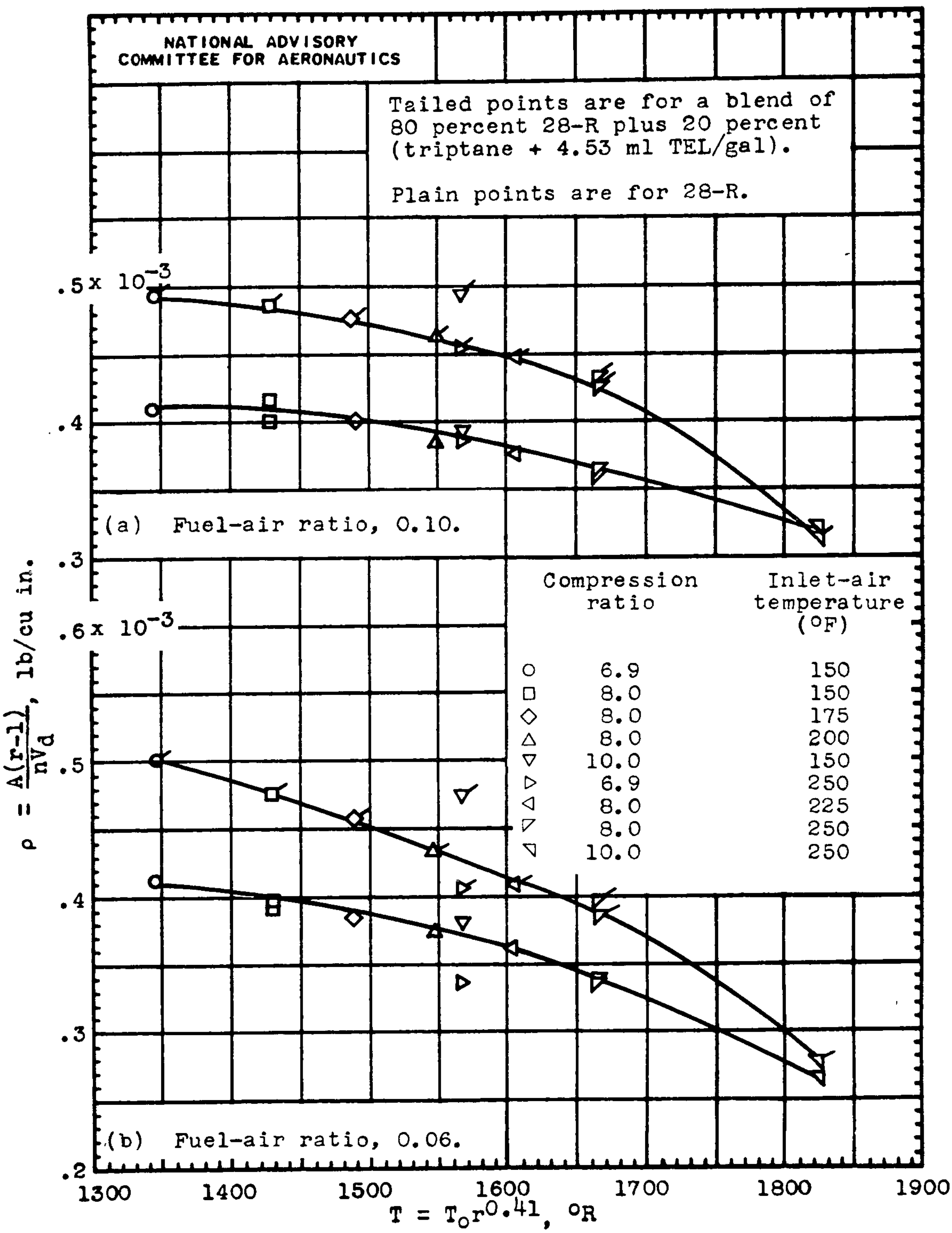


Figure 8. - Temperature-density relations for two fuels at a spark advance of 20° B.T.C. R-2600 cylinder; engine speed, 2100 rpm; rear spark-plug-bushing temperature, 450° F. Unpublished data.

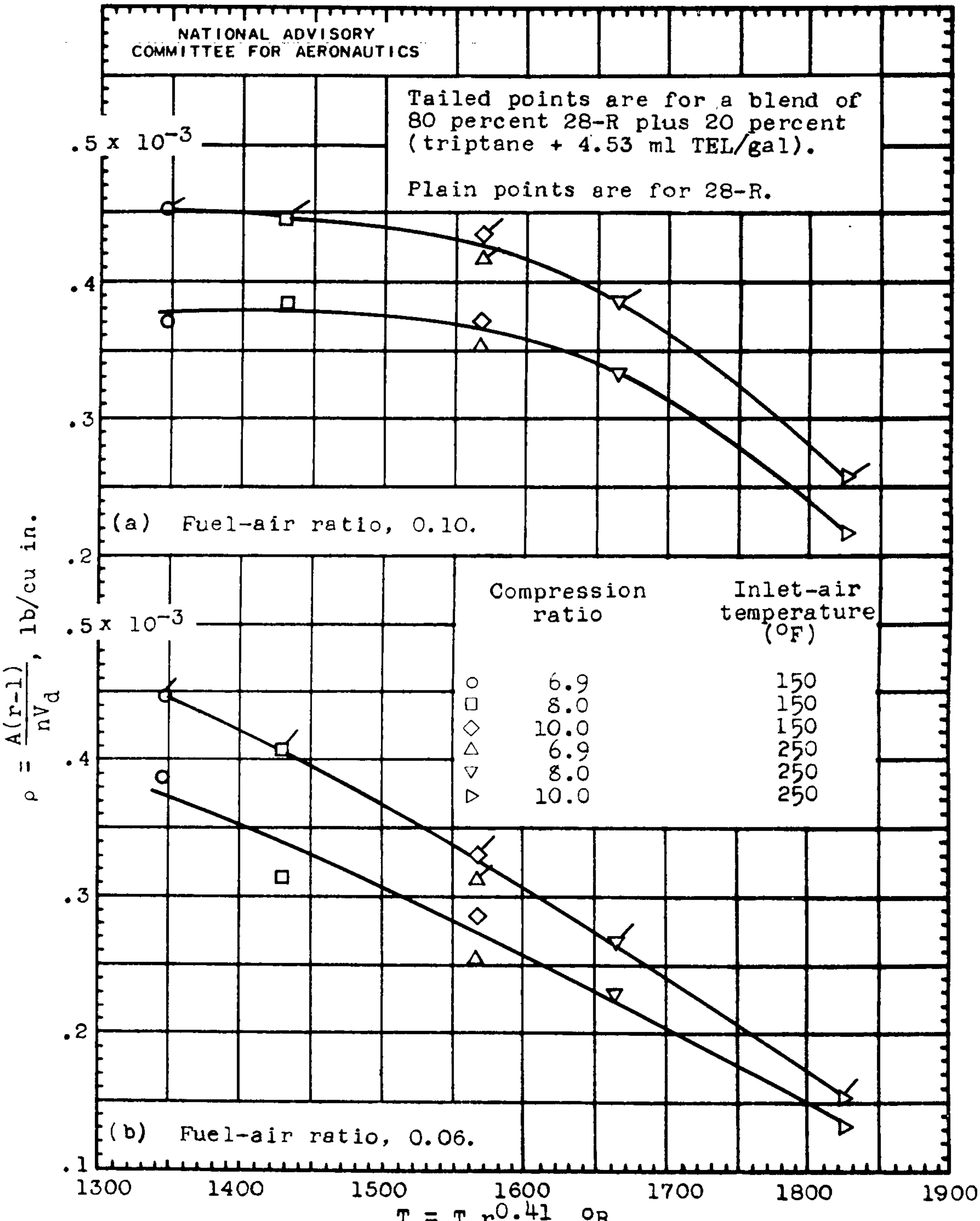


Figure 9. - Temperature-density relations for two fuels at the spark advance for maximum economy. R-2600 cylinder; engine speed, 2100 rpm; rear spark-plug-bushing temperature, 450° F. Unpublished data.

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